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Small angle crab compensation for LHC IR upgrade

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DISCLAIMER

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Abstract

A small angle crab scheme is being considered for the LHC luminosity upgrade. In this paper we present a 400MHz superconducting cavity design and discuss the pertinent RF challenges. We also present a study on the beam-beam performance and proton-beam emittance growth in the presence of crab compensation, with RF noise sources.

INTRODUCTION

A small angle ($<$ 1mrad) crab scheme is an attractive option for the LHC luminosity upgrade to recover the geometric luminosity loss from the finite crossing angle [1]. The luminosity loss increases steeply to unacceptable levels as the IP beta function is reduced below its nominal value (see Fig. 1 in Ref. [2]). The crab compensation in the LHC can be accomplished using only two sets of deflecting RF cavities, placed in collision-free straight sections of the LHC to nullify the effective crossing angles at IP1 & IP5. We also explore a 400 MHz superconducting cavity design and discuss the pertinent RF challenges. We present IR optics configurations with low-angle crab crossing, study the beam-beam performance and proton-beam emittance growth in the presence of crab compensation, lattice errors, and crab RF noise sources.

CAVITY OPTIMIZATION

A parametrization developed in Ref. [3] for elliptical cavities was used to tune the half-cell shape for optimum RF properties. The two-cell cavity is constructed from two identical inner half cells and two end half cells. which are tuned to compensate for the frequency shift due to the beam pipe. Each half cell can be constructed with the geometrical parameters given in Ref. [3]. The final design of the two-cell cavity is shown in Fig. 1 with the respective geometrical values listed in Table 1. For pertinent RF parameters such as R/Q, peak fields, and cell to cell coupling, the cell shape was optimized for both TM_{110} and TM_{010} modes which are shown in Fig. 2. This optimization is required to reduce the ratio of the kick voltage to the peak surface fields which are usually much larger for the TM_{110} mode compared to the usual accelerating cavities. Some issues of the cavity design still under investigation include:

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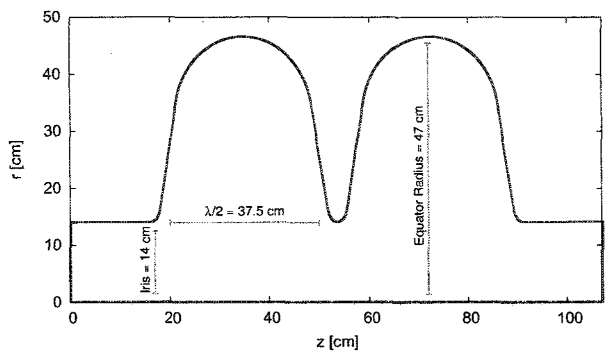

Figure 1: Optimized two-cell design for 400 MHz TM_{110} cavity.

- Careful analysis of higher order modes is needed to determine the final beam pipe radius which will allow all HOMs to propagate via the beam pipe to a ferrite load.
- A KEK type coaxial coupler optimized for 400 MHz to damp the TM_{010} (lowest mode) which can also be used for frequency tuning of the deflecting mode. A modification of the KEK design is needed to make this damping approach more robust.

Table 1: Cavity geometrical parameters

Parameters	Mid Cell	End Cell
Frequency [MHz]	400	400
Iris Radius, R_{iris} [cm]	14	14
Wall Angle, α [deg]	10	10
Equatorial Ellipse, $R = B/A$	1.0	1.0
Iris Ellipse, b/a	1.5	1.5
Cavity wall to iris plane, d [cm]	1.5	1.5
Half Cell, $L = \lambda\beta/4$ [cm]	18.75	18.75
Equator Height, D [cm]	50	50
Cavity Beta, $\beta = v/c$	1.0	1.0

CRAB RF PHASE NOISE

A phase error in the RF wave causes an offset of the bunch rotation axis translating into a transverse offset at the IP as shown in Fig. 3. The IP offset is given by

$$\Delta x_{IP} = \frac{c\theta_c}{\omega_{RF}}\delta\phi \tag{1}$$

where θ_c is the full crossing angle and $\delta\phi$ is the phase error.

The random offset at the IP due to beam-beam effects and additional random dipole kicks due to crab phase jitter can be potentially detrimental to the beam emittance.

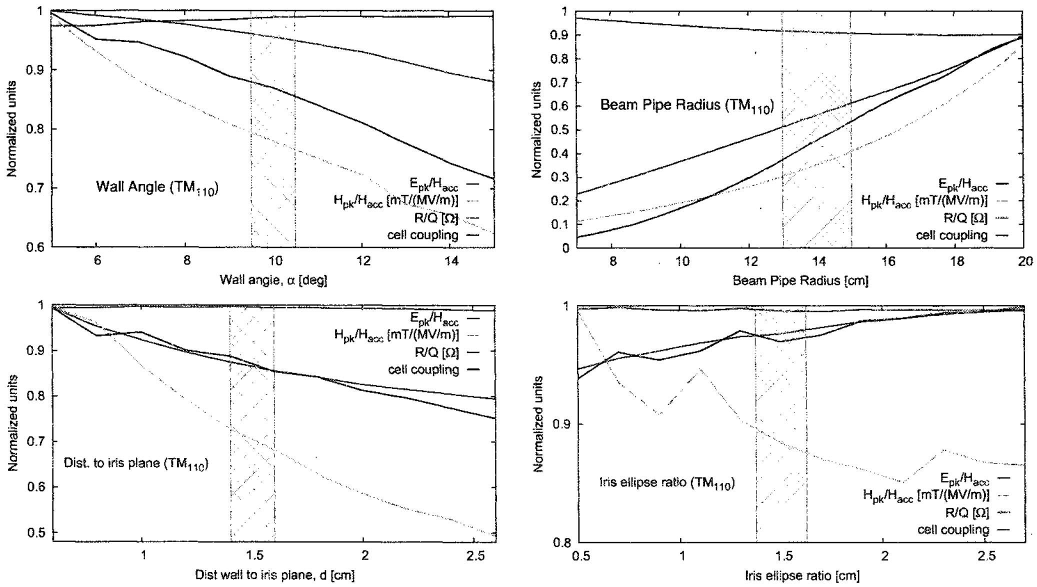

Figure 2: Pertinent RF parameters like R/Q, peak fields and cell-to-cell coupling as a function of the geometrical parameters for TM_{110} mode.

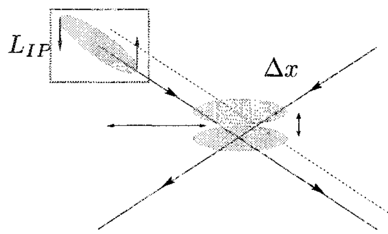

Figure 3: Effect of phase jitter on the crab compensation which results in a transverse offset of the bunch at the IP.

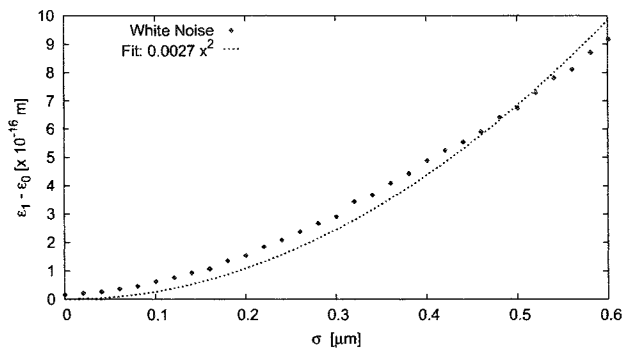

Figure 4: Emittance growth for a white noise type beam-beam offset at the IP ($\beta^* = 0.25m$) for two IPs as a function of noise amplitude. The solid line is a quadratic fit to the simulated data.

The emittance growth resulting from the beam-beam forces an due to random dipole kicks including damping and decoherence and feedback can be pessimistically estimated as [4, 5]

$$\left(\frac{\Delta\epsilon_x}{\Delta t}\right) \approx f_{rev}\frac{1-s_0}{4}\frac{\Delta x^2}{\sigma_x^{*2}}\left(\frac{1}{1+\frac{g}{2\pi\xi}}\right)^2 \quad (2)$$

where g is the feedback gain factor (~0.2), $|\xi|$ is the the total beam-beam parameter (~0.1), σ_x^* is the horizontal IP beam size, and s_0 is a constant (~0.6).

Multi-particle simulations in the presence of beam-beam (weak strong) with LHC upgrade optics ($\beta^* = 0.25$m) at 2 IPs were performed and Fig. 4 shows a white noise induced emittance growth as a function of the offset amplitude. A quadratic fit suggests a tolerance on white noise to be $\sigma_{noise} = 1.98\ nm$ for a 1% emittance growth per hour. However, measurements of the phase jitter from the KEK-B crab cavities show that the noise modulation is not "white" but has a frequency spectrum as shown in Fig. 5. Sidebands of -65 db below the main RF signal are visible in a 200 Hz span (32Hz, 37Hz, 46Hz, 50Hz, 100Hz) and sidebands almost -80db down are visible in a 200 kHz span (32 kHz, 64kHz). A wider span of 3MHz shows no sidebands above the noise level. Simulations were also performed with beam-beam offsets with frequency dependent noise like the ones in Fig. 5. Fig. 6 shows the emittance growth as a function of the amplitude for three different sine like modulated noise similar to the ones observed in the KEK cavities. A quadratic fit to the 32KHz (one of the fast frequencies observed in KEK-B) line suggests a maximum $\sigma_{noise} \approx 6 \times 10^{-12}$ m for an emittance growth of 1% per hour. An amplitude of -80db of the noise source translates to an IP offset of 0.6×10^{-12} m which is an order of magnitude smaller than maximum tolerance of 1% emittance growth per hour.

Also, preliminary simulations in Ref. [6] suggests that the tolerances can be relaxed linearly with correlation time of the noise source. Since the slow noise sources are the dominant ones, the phase tolerance should be less stringent. In addition a transverse feedback alleviates some of

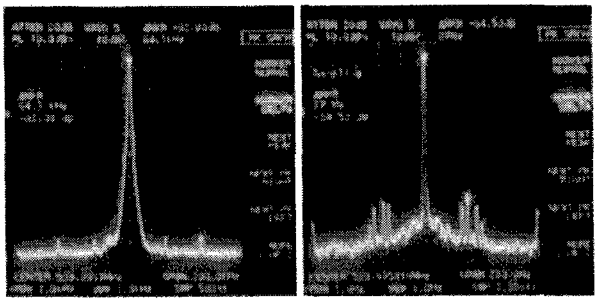

Figure 5: Phase noise measured from the KEK-B crab cavities from the pick-up probe during operation at low intensity. Sidebands are visible at 32kHz range (fast, left plot) and 50Hz range (slow, right plot) at -80db and -65dB in amplitude compared to the central 509 MHz signal (Courtesy KEK crab cavity group).

the tightest requirements. Some analytical estimates of tol-

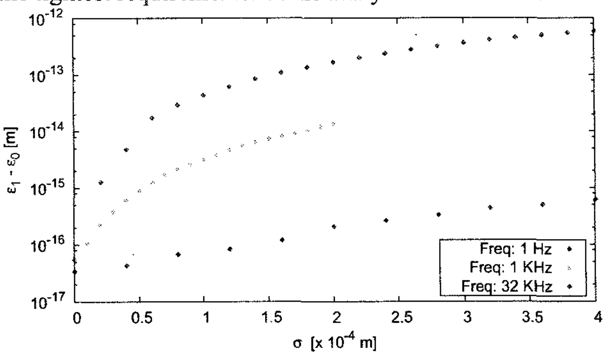

Figure 6: Emittance growth for beam-beam noise offset at two IPs with different modulation frequencies (1 Hz, 1KHz, and 32 KHz) at the IP ($\beta^* = 0.25m$) as a function of modulated amplitude.

erances and those derived from simulation are listed and compared in Ref. [1].

PROTOTYPE, PHASE I AND II

A 800 MHz superconducting prototype is foreseen to test a variety of SRF issues, some which are outlined in section . Other outstanding issues to be addressed are:

- Test of main components (Input coupler, coaxial damper, HOM damping etc..)
- Study of Q_0 degradation, field emission, maximum achievable surface fields, multipacting and others for a cavity operating in the TM_{110} mode.
- RF controls, phase stability, cavity tuning and mechanical issues related to cavity and cryostat.

There is a clear advantage of a global crab compensation scheme since it requires fewer cavities and allows some freedom in their location due to the large transverse size of the 400 MHz deflecting elliptical cavities. However, it was concluded in [1] that for large crossing angles (> 2 mrad), only local crab compensation in the interaction region is possible. This is needed to keep the orbit and tune excursion due to crab cavities placed elsewhere in the ring to an acceptable level. Based on these criteria, the future development of the crab cavities can also be classified into two phases, and also synchronized with the LHC upgrade phases I and II [7].

- Phase I: Since, the upgrade only includes minimal modification of the IR magnets a global crab crossing scheme similar to KEK-B offers a relatively simple solution to recover the geometric reduction. This is compatible with all the quadrupole first options being considered for the phase I upgrade.
- Phase II: This upgrade entails a complete redesign of the IR. Therefore a local compensation with larger crossing angle (4-6 mrad) can be considered if either the bunch length is shortened or a more compact design of the cavity is available. This scheme will alleviate long range beam-beam issues which can be a main limitation for parameters foreseen for phase II.

CONCLUSIONS

A low angle global crab compensation scheme is very attractive for the phase I upgrade of the LHC to recover the geometric reduction of luminosity. An optimized design of a 400 MHz two-cell cavity is presented. Crab RF phase noise tolerances from modulated noise sources as observed in KEK-B crab cavities are less stringent almost by an order of magnitude than what was conceived before. A prototype is essential to test the new optimized design for several RF and mechanical issues.

ACKNOWLEDGMENTS

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